



Status of Experiments Hosted by the Particle Physics Directorate

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1/9/24

Introduction

The Particle Physics Directorate is the scientific home of our core experimental HEP program

- Operating experiments in Neutrinos, Muons, CMS, and Astrophysics
- Supported by the same expert staff and facilities that build our highest priority projects (See June 2022 PAC report)
- Close collaboration with theory group (see June 2023 PAC report)
- Partner with other directorates for scientific and technical expertise



Introduction

- Following the P5 report in 2014, FNAL has followed a consistent strategy across our HEP research program
- Pursue the relevant science drivers
 - ✓ Use the Higgs boson as a new tool for discovery
 - ✓ Pursue the physics associated with neutrino mass
 - ✓ Identify the new physics of dark matter
 - ✓ Understand cosmic acceleration: dark energy and inflation
 - ✓ Explore the unknown: new particles, interactions and physical principles
- Execute specific recommendations of the P5 report
 - ✓ Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the HL-LHC upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS).
 - ✓ Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.
 - ✓ Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.
 - ✓ Recommendation 18: Support CMB experiments as part of the core particle physics program.
 - ✓ Recommendation 19: Proceed immediately with a broad second-generation (G2) dark matter direct detection program
 - ✓ Recommendation 22: Complete the Mu2e and muon $g-2$ projects.



Neutrino Science

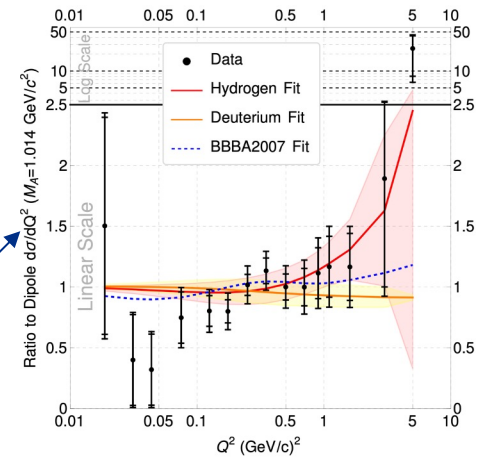
Neutrino Science: Status of experiment operations

Experiment	Start of Operations	End of Operations	Status
MINERvA	2010	2019	Analyzing/Publishing
MicroBooNE	2015	2020	Analyzing/Publishing
NOvA	2014	---	Running, Analyzing/Publishing
ANNIE *	2021 (Phase-II)		Running, Analyzing/Publishing
ICARUS	2021	---	Running, Analyzing/Publishing
SBND	2024 (expected)	---	Completing Installation and Commissioning

*= covered in a separate talk

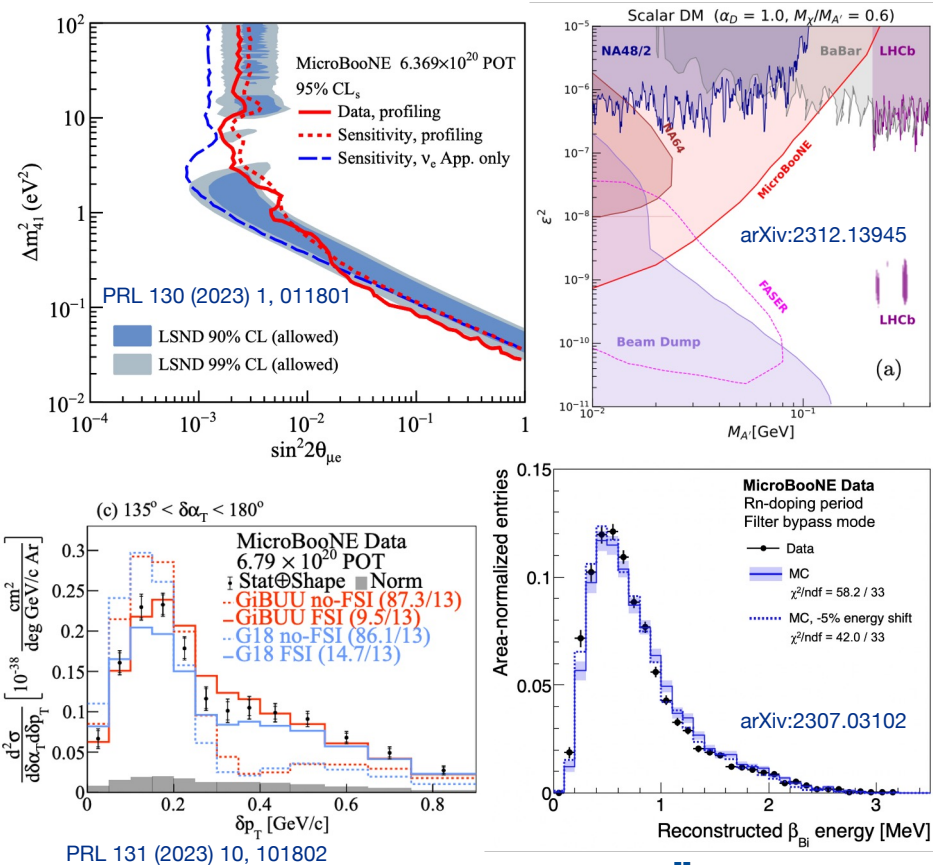
Neutrino Science: MINERvA

- High statistics measurements of ν and anti- ν to understand role of nucleus in the interaction channels that are key to DUNE's oscillation measurements
- Run ended in 2019, still publishing! 7 results in 2023:
 - Scattering on H to measure Axial form factor **Nature**, 614, 48-53 (2023)
 - 2 Anti- ν Quasielastic scattering on Carbon:
 - 2-dimensional cross section vs. muon kinematics **Phys. Rev. D** 108, (2023) 032018
 - Multi-neutron cross section **Phys.Rev.D** 108, (2023) 112010
 - ν Quasielastic scattering on nuclear targets **Phys. Rev. Lett.** 130, 161801 (2023)
 - Pion production on nuclear targets **Phys. Rev. Lett.** 131, 051801 (2023), **Phys. Rev. Lett.** 131, 011801
 - NuMI flux from both ν & anti- ν scattering on electrons **Phys.Rev.D** 107 (2023) 1, 012001
- 2024 publication plans include:
 - Electron neutrino and antineutrino cross sections [arXiv:2312.16631](https://arxiv.org/abs/2312.16631)
 - Novel measurements of charged and neutral pion production
 - Shallow Inelastic Scattering, Searches for new physics
 - Completion of data processing campaign and data preservation plan



Neutrino Science: MicroBooNE

- World's most scientifically productive LArTPC experiment with over 60 papers, including 10 in the last year
- Demonstrating the versatility and power of liquid argon for SBN and DUNE
 - Constraints on light sterile neutrinos
 - Innovative BSM and cross section programs
 - MeV-scale physics capabilities
- Major new analyses in progress
 - First full-dataset analyses
 - Groundbreaking joint BNB+NuMI sterile neutrino oscillation search
 - Searches for alternative explanations for the MiniBooNE low energy excess (e.g. overlapping e^+e^- pairs)



Neutrino Science: NOvA

- Doubled (1.96x) FHC(v) dataset at the end of FY23 accelerator run. Returning to RHC (anti-v) running in FY24
- 3 papers published in 2023, 2 more under journal review.

At right: figure from paper on Bayesian re-analysis of 2020 dataset, arXiv:2311.07835

- Looking ahead to 2024, we anticipate:

New 3-flavor oscillation results with double the FHC data.

Results from the joint fit with T2K

New cross section measurements

New BSM search

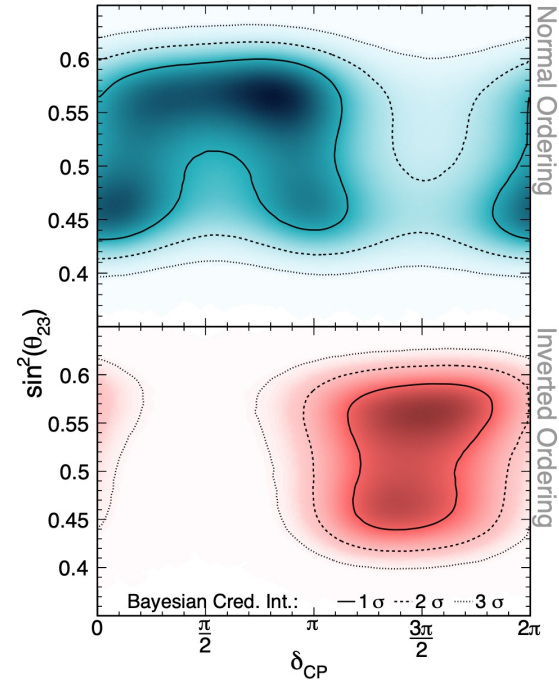


FIG. 7: Binned posterior probability density (shaded) with 1, 2, and 3 σ credible intervals for $\delta_{\text{CP}} - \sin^2 \theta_{23}$, marginalized over both mass orderings for the normal mass ordering (top, blue) and the inverted mass ordering (bottom, red). In this fit a Gaussian θ_{13} prior from reactor experiments was applied.

Neutrino Science: ICARUS early results and plan for publications



Structure of one module with 2 TPC chambers

- ICARUS 760 LAr-TPC detector was successfully operated at Gran Sasso Lab from 2010 to 2013, exposed to CNGS neutrino beam from CERN.
- New ICARUS shallow depth operation at FNAL exposed to lower energy Booster and NuMI neutrino beams:
 - The detector was overhauled at CERN, transported to Fermilab and installed in 2018-'20;
 - ICARUS successfully taking data with both Booster and NuMI neutrino beams since June '21
 - Recent detector improvements on LAr purity, electronics noise of the TPC, new PMT cabling and trigger system for an excellent beam exploitation

- **Initial ICARUS detector published papers:**

Babicz M. et al., *JINST* **13** P10030 (2018) on new photomultiplier tubes;

Bagby L. et al., *JINST* **13** P12007 (2018) on new TPC read-out electronics;

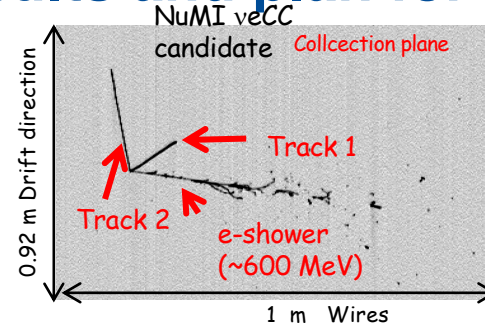
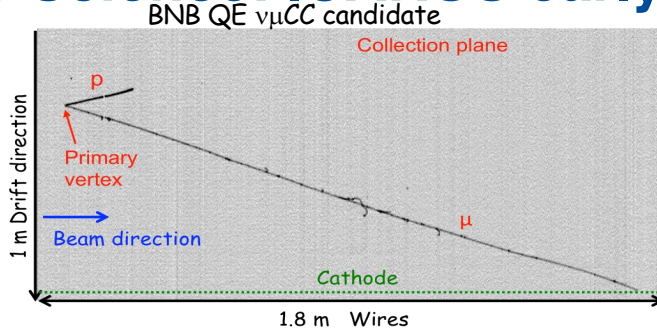
Ali-Mohammadzadeh B. et al., *JINST* **15** T10007 (2020) on new PMT system implementation;

Bagby L. et al., *JINST* **16** P01037 (2021) on TPC read-out electronics installation;

Abratenko, P. et al., ICARUS at Fermilab Short-Baseline Neutrino program: initial operation, *Eur. Phys. J. C* **83**, 467 (2023).

- **Forthcoming technical papers on:** *Cryogenics and LAr purification systems, Cosmic Ray tagger system, Trigger system.*

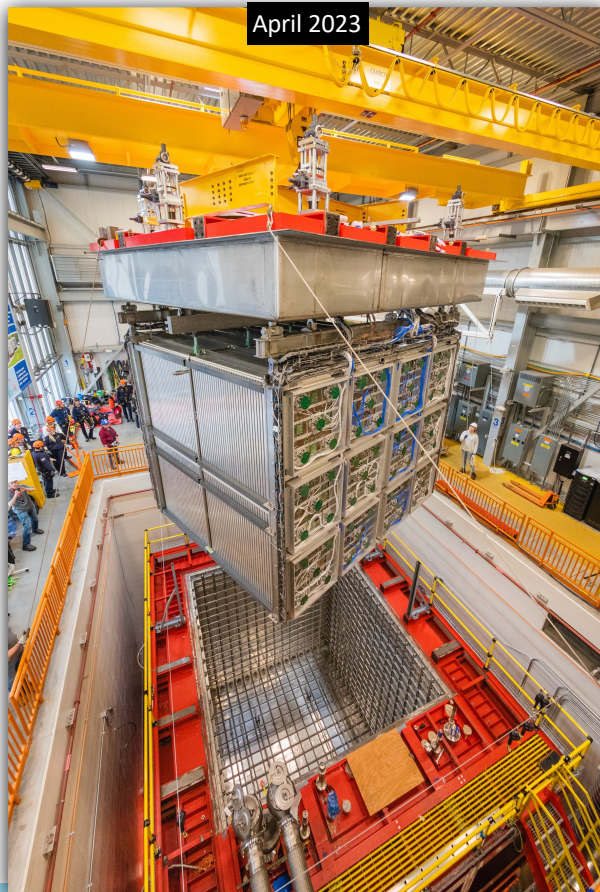
Neutrino Science: ICARUS early results and plan for publications



- High quality of collected events: initial ICARUS only ν_{μ} and ν_e physics analysis and BSM searches with collected BNB ($2.5 \cdot 10^{20}$ PoT) and NuMI ($3.5 \cdot 10^{20}$ PoT) data (results expected in 2024):
 - Ongoing investigation of $e\nu$ anomalous oscillation of Neutrino-4 claim with BNB ν_{μ} disappearance and then with ν_e from NuMI;
 - Neutrino cross section measurements with NuMI off-axis beam;
 - BSM studies in dimuon channel with NuMI off-axis beam.
- Calibration studies, detector physics (papers in preparation):
 - *Energy scale calibration and angular dependent electron-ion recombination;*
 - *Longitudinal and transverse diffusion of ionization electrons;*
 - *LAr temperature dependence of ionization electron drift velocity;*
 - *Wire signal equalization, signal and noise modeling in the ICARUS TPC;*
 - *Prediction of NuMI electron and muon neutrino flux in ICARUS.*
- Anticipating neutrino oscillation studies together with the SBND detector.

Neutrino Science: SBND

- The TPC/Photon systems are installed inside the cryostat, and the detector systems have been cabled.
- Cosmic Ray Tracker is partially installed and will be completed by summer (must be staged around TPC commissioning).
- The cryostat/cryogenic system was completely closed off in December. Completion of ORC for cryogenic system expected 2nd week of January.
- Then begins the piston purge of the cryostat using argon gas to remove impurities, followed by cool down.
- Liquid argon fill scheduled to begin in February, taking ~3 weeks to fill. Argon delivery contract is in place.
- Detector commissioning will begin once full with stable LAR



Detector rigging into the cryostat



CRT north wall installation



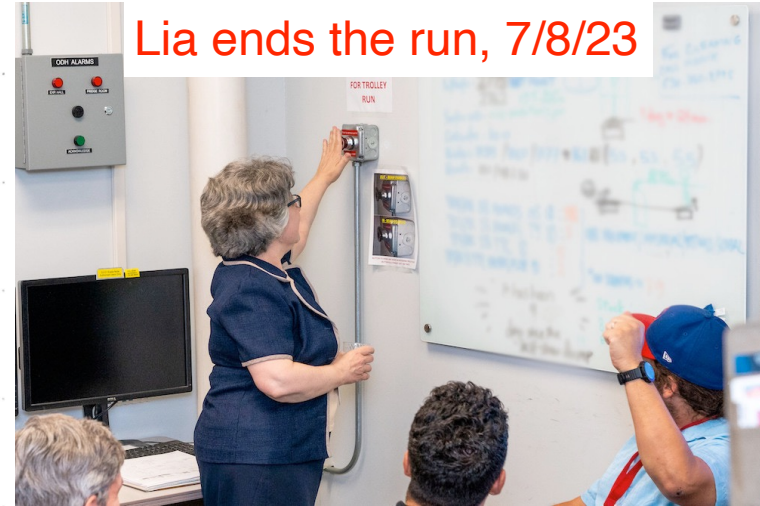
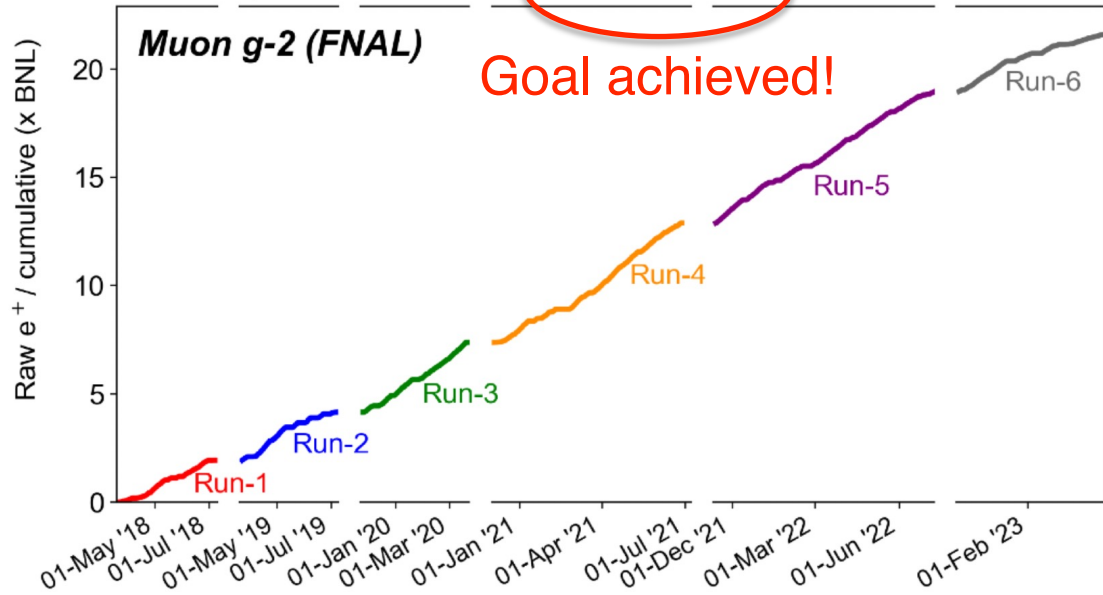
Cabling and cryogenic connections



Muon Science

Muon Science: g-2 operations

Last update: 2023-07-06 11:25; Total = 21.90 (xBNL)

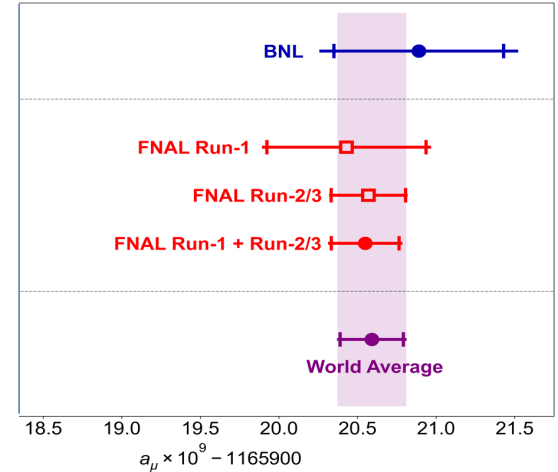


- g-2 ended operations at the end of the FY23 accelerator run
- Currently completing final systematic studies before warming the ring at the end of January

Muon Science: g-2 outlook

• Second result from Run-2/3 data

- Second result garnered world-wide media attention with **2,000+ media mentions and 7+ billion media reach**
- Run-2/3 **result agrees well** with FNAL Run-1 and BNL
- New average has **190 ppb** precision, dominated by FNAL
- Systematic uncertainty of **70 ppb** already surpasses goal
- Theory comparison challenged by discrepancy between e+e- data and Lattice as well as recent CMD3 result
- Updated SM prediction expected in 2025 using all available data will **likely yield a smaller and less significant discrepancy**



• Outlook

- Data from **Run-4/5/6 fully produced** and analysis making good progress
- With more than 21x BNL statistics on tape we will likely surpass total precision of **140 ppb**
- Plan to **publish result of the full dataset in 2025** with twice improved statistical precision
- **Other analysis ongoing** with first results based on Run-1 data expected in 2024:
 - Muon Electric Dipole Moment analysis with final sensitivity goal of $\leq 10\text{-}20 e\cdot\text{cm}$
 - BSM searches via CPT/Lorentz violation and Dark Matter

Energy Frontier Science

Energy Frontier Science: CMS Run 3 Operations (1)

- LHC Run 3 plan had to be modified due to challenges encountered in 2023
 - Only 48 days of pp physics (97 planned) (32/fb delivered vs 75/fb expected)
 - 32 days of PbPb HI run instead of the 27 days PbPb and special runs (high beta and VdM scans)
- CMS detector performed well in 2023 (92% efficiency in pp running – 29/fb recorded)
- The LHC is currently in the year end technical stop
 - Expected start of commissioning in March 2024, physics data in April 2024
- LHC is proactive in fixing problems that caused significant restrictions of machine intensities in 2023 and the Run 3 plan is being adjusted to mitigate the major loss of pp physics time
 - 115 (145) days of pp run in CY24 (CY25)
 - Total Run 3 pp integrated luminosity of > 260/fb expected

Energy Frontier Science: CMS Run-3 Operations (2)

- Performance of Fermilab Computing facilities (Tier-1 and Analysis Facilities) remains excellent
Resources needed for Run3 were in place just in time, despite many challenges (increased HW cost, limited availability, procurement delays)
- Fermilab HEP-Cloud provides CMS with significant HPC allocations at DOE and NSF facilities
Now important part of CMS production CPU resources, fully integrated into production workflows
- USCMS 2023 survey showed that our community is well supported in their analysis activities
Fermilab is playing a prominent role: majority of analysts listing LPC as their preferred location
LPC interactive login cluster, LPCCAF batch system and data storage are vital to the community
- New Elastic Analysis Facility available to CMS, optimized for columnar analysis, enjoys increasing attention and utilization
Future of data analysis is being developed at Fermilab and US Tier-2s, Fermilab is home to Coffea, the columnar analysis toolkit
- Dedicated support personnel at Fermilab and the LPC is key to US CMS operation success, strengthened in 2023 (added personnel to support GPU adaptation, and detector ops.)

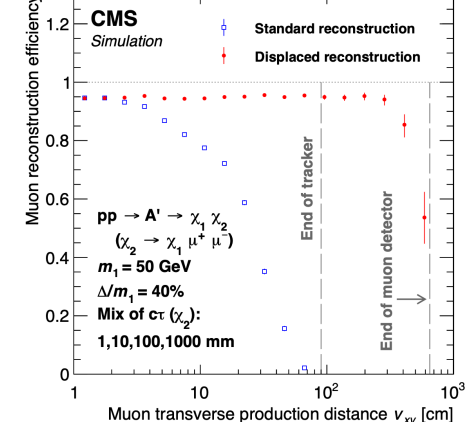
Energy Frontier Science: CMS results and FNAL contributions (1)

- CMS has published 1239 papers with collider data (highest # of publications from a single experiment), documenting innovative searches for new phenomena and precision SM measurements

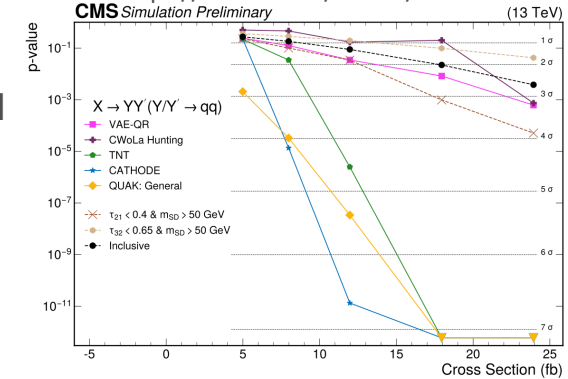
The Fermilab group, in partnership with the LPC, made major contributions to ~30% of the CMS papers (~320 papers)

- FNAL physics strategy:
 - capitalize on the group's expertise in advanced experimental techniques (e.g. using the detector beyond specs and deploying AI/ML at all stages of the data taking, reconstruction, analysis)
 - maintain a prioritized portfolio of new ideas targeting non-standard BSM signatures, while continuing to lead some of the classic analyses
- In the past year, FNAL group has led 16 CMS papers, over 20 limited authorship papers (and 46 white papers in the context of the Snowmass process)

<https://arxiv.org/pdf/2305.11649v1.pdf>



<https://cds.cern.ch/record/2881089>



Energy Frontier Science: CMS results and FNAL contributions (2)

- First dedicated collider search for inelastic Dark Matter

Probes for the existence of a dark sector communicating to the SM through a vector portal (striking signature with a pair of almost collinear, low-momentum and displaced muons)

Featured in the [CERN courier](#) and published in [Phys. Rev. Lett.](#)

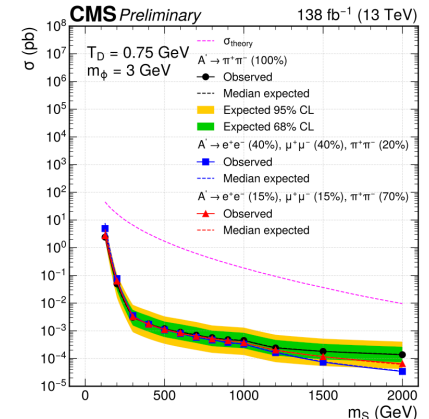
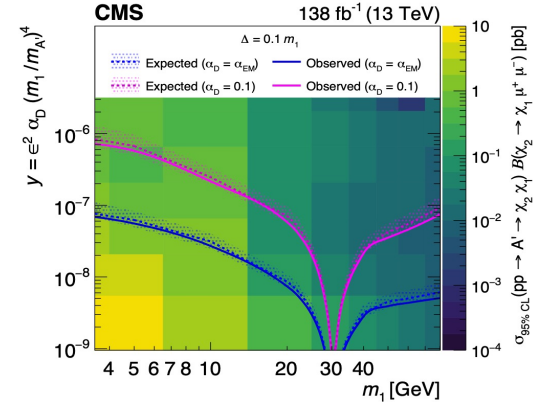
- First dedicated search for soft unclustered energy patterns or SUEPs

Targeting Hidden Valley models with a new, confining force with a large coupling leading to large multiplicity of low-momentum, diffuse, charged particles in the final state

<https://cds.cern.ch/record/2883117>

- Search for long-lived particles using a novel technique, based on trackless and out-of-time jet information combined in a deep neural network discriminator

<https://arxiv.org/abs/2212.06695>, published in JHEP



Energy Frontier Science: response to PAC recommendations

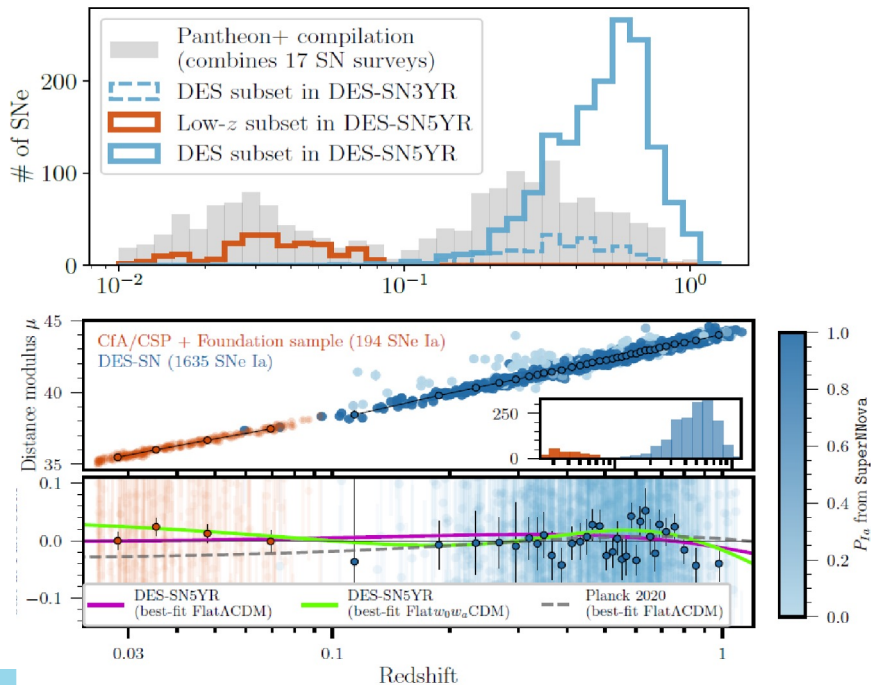
1. Fermilab streamline site access for US CMS collaborators so that they can easily access the LPC and ROC Fermilab has been working on implementing site access controls to be compliant with DOE directives while enabling the organization to achieve its mission. Members of our group are providing feedback and working closely with senior lab management to improve site access policies and procedures.
2. Fermilab should work with DOE to restore adequate funding for the LPC to rebound The laboratory has submitted a request for increased funding through the standard Field Work Proposal process.
3. The LPC ensures regular on-site presence of Fermilab-based experts Several actions had been taken to re-establish on-site presence of Fermilab-based experts (including targeted recruitments of LPC Distinguished Researchers candidates, programmatic selection of DRs, enhanced support to ROC operations).
4. The US CMS investigates ways to expand the usage of the Fermilab ROC to help alleviate the current shortage of shifters at CERN In collaboration with the USCMS Operations Program, the Fermilab group has developed a plan to increase USCMS personnel at Fermilab to support shift taking, modernize the space, and provide on-site housing options
5. The Fermilab CMS group has a stable presence at CERN sufficient to contribute to data-taking operations with experts on shift and on call In addition to permanent personnel at CERN (newly hired senior application physicist taking a major role in detector operations), the group has supported travel of a larger than usual number of physicists taking shifts at P5. Through this model, the Fermilab group has met the requirements for CY23.

More detailed answers have been provided to the PAC.

Cosmic Science

Cosmic Science: DES

- DES remains very productive: 33 papers submitted in 2023, spanning astrophysics/cosmology
- DES Full 5 Year SNe Ia Cosmology Results



- 1650 photometrically-typed SNe Ia

- More SNIa than all previous SN cosmology combined & 5X world sample at $z > 0.5$
- Exquisite control over systematics in Hubble Curve

- Best SNe Ia cosmology results from SN:

- Flat Λ CDM: $\Omega_m = 0.352 \pm 0.017$

- Flat w CDM:

$$(\Omega_m, w) = (0.264^{+0.074}_{-0.096}, -0.80^{+0.14}_{-0.16})$$

- Flat w, w_0, w_a CDM:

$$(\Omega_m, w_0, w_a) = (0.495^{+0.033}_{-0.043}, -0.36^{+0.36}_{-0.30}, -8.8^{+3.7}_{-4.5})$$

Cosmic Science: DES

- Transferring data service from NCSA to FNAL
 - NCSA expects to be able to serve DES data through Late Summer 2024.
 - Fermilab has agreed to consolidate and provide longer term support for a ½ to 1 Peta-byte store of image-level & database-level specialty cosmology-quality data products currently being produced and/or stored in multiple domains, including NCSA.
 - Feasibility tests are near completion. We're also near to having a timeline for operation at FNAL.
- Transferring darkenergysurvey.org website service from DES Collaboration to FNAL
 - DES Collaboration funds are paying for a now expensive service but can't do that for much longer
 - Fermilab will host the website using "standard" resources at no cost to the experiment or Ops
 - Transfer of website is essentially complete. Some features/apps need to be replaced. Testing underway.
 - Switchover this spring expected to be seamless

Cosmic Science: SENSEI

- SENSEI@SNOLAB

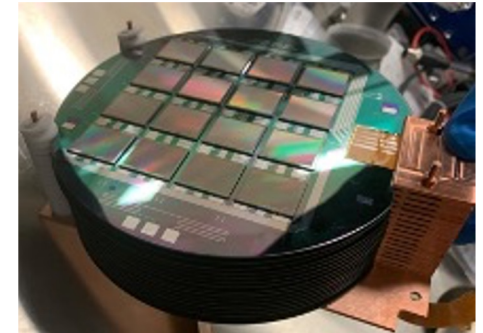
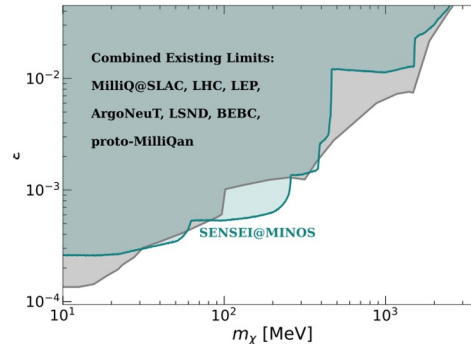
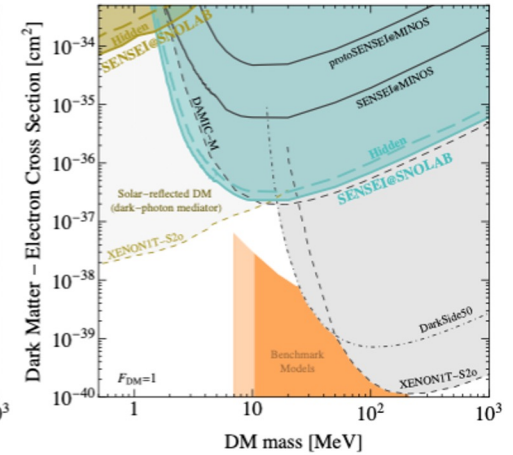
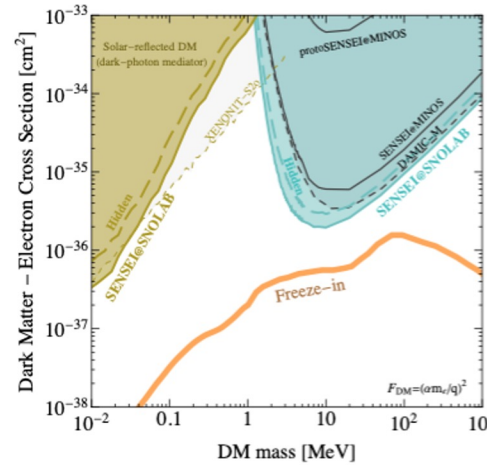
100g Skipper CCD experiment

New results released in December setting world leading limits on DM (arXiv: 2312.13342)

- SENSEI@MINOS

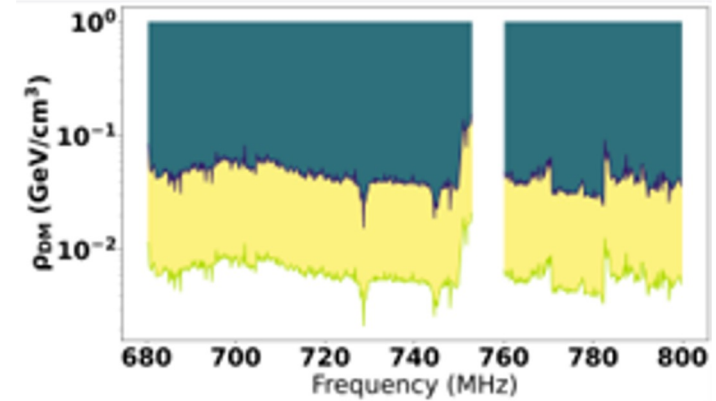
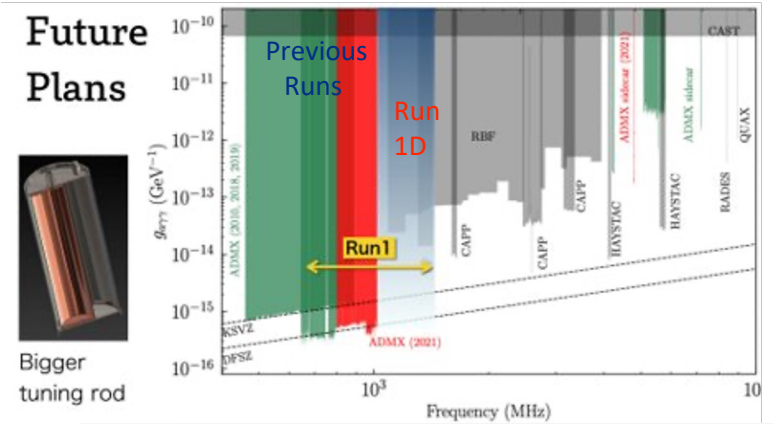
World-leading limits in search for Millicharged Particles produced in the NuMI Beam with 2g (arXiv: 2305.04964)

- OSCURA will scale from 50 CCDs in SENSEI to 24,000 CCDs to accumulate target mass.

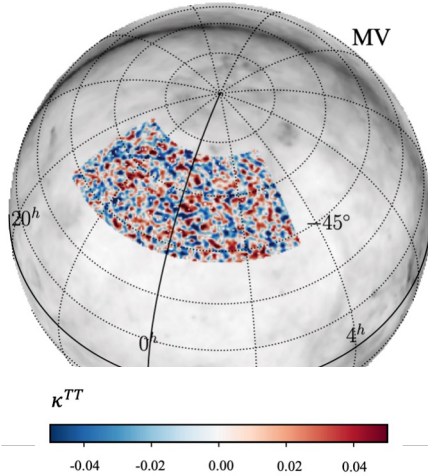


Cosmic Science: ADMX

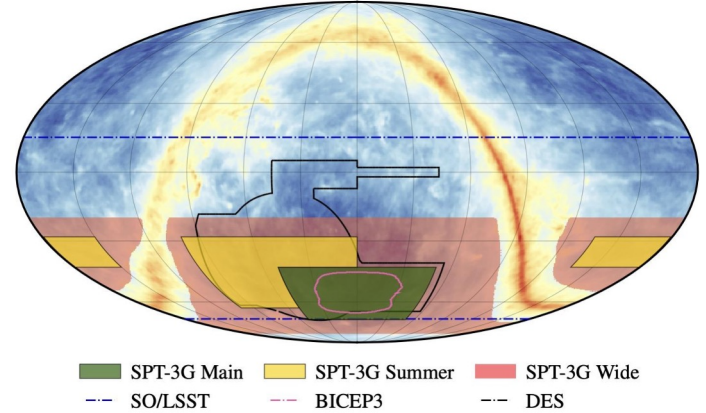
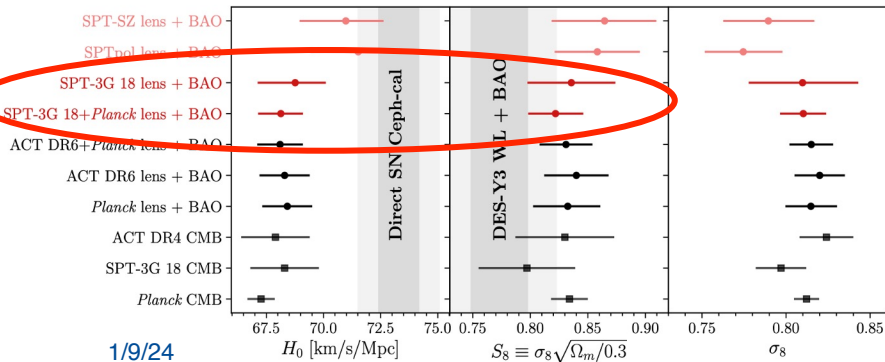
- ADMX-G2 began a two-year run in December (Run 1D) searching for the QCD axion in the 1020-1390 GHz region.
- Recent publications
 - “Axion Dark Matter eXperiment: Run 1D analysis details”, C. Boutan et al., Phys Rev D.
 - Submitted: Non-Virialized Axion Search Sensitive to Doppler Effects in the Milky Way Halo by Bartram C., Braine T, et. al., Phys Rev D.
- Implementing improvements in ADMX based on R&D for ADMX-EFR
- Fermilab PW8 Hall has been cleaned up in preparation for installation of ADMX-EFR experiment.
- Preparing to install 9.4 Tesla MRI magnet.



Cosmic Science: SPT-3G Status and CMB Lensing Results



- First *measurement of CMB gravitational lensing with SPT-3G*: [Pan et al. 2023](#)
PRD Editors Suggestion
- Cosmological constraints consistent with Λ CDM and other CMB measures; slight tension with “local probes” (e.g., DES 3x2) remains



- **SPT-3G spending 2024 observing a new 10,000 deg² “Wide” field:**

- Improves SPT-3G cosmological constraints by reducing sample variance from larger sky area.

- **Major SPT-3G data releases in 2024 include:**

- 2019+2020 TT/TE/EE power spectrum and CMB lensing and cosmological constraints
- High- ℓ (small-scale) TT power spectrum (Led by **FNAL SCGSR *Dibert***)
- First galaxy cluster catalog from SPT-3G (Led by **FNAL PD *Sobrin***).
- Low- ℓ (large-scale) BB polarization power spectrum (Led by **FNAL PD *Zebrowski***)

Cosmic Science: SPT-DES: Cross Correlations of Lensing & Clusters

- Cross-correlation of the **DES-SPT gravitational lensing data**, analysis co-led by Omori and Chang (both at UChicago)
- Hints at the solution to one current cosmological tension, finding that “galaxy lensing” measures systematically lower structure growth
 - [Omori et al. 2023, PRD](#)
 - [Chang et al. 2023, PRD](#)
 - [Abbott et al. 2023, PRD](#)

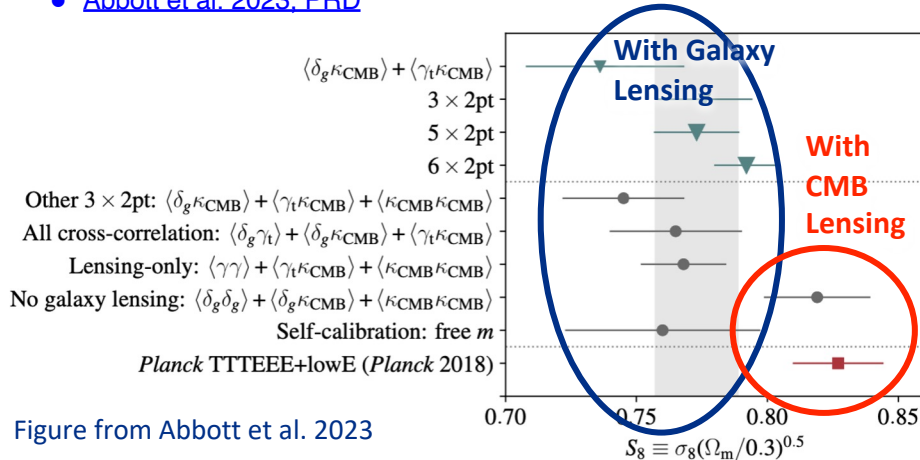
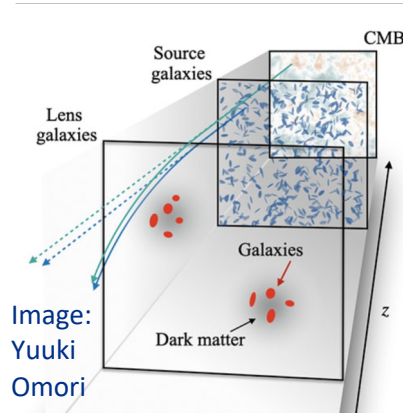
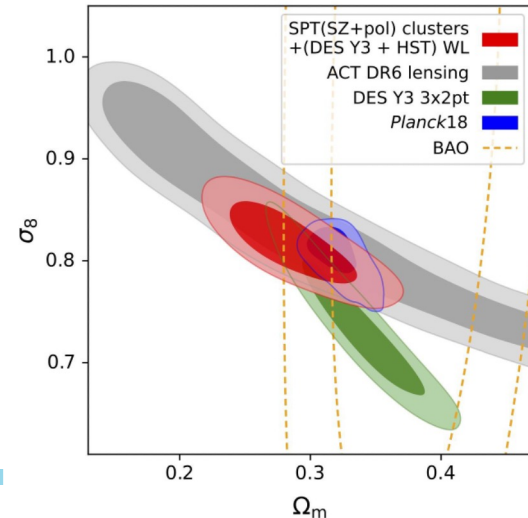


Figure from Abbott et al. 2023

- **SPT+DES galaxy cluster analysis** has led to tightest cluster-based cosmological constraints yet ([Bocquet et al. 2024](#)).
- Consistent with Λ CDM, used to put upper limit on the sum of neutrino masses of < 0.18 eV (at 95% confidence) from joint CMB+Clusters analysis.



Other Experiments

SpinQuest Status

- SpinQuest is on track to begin operations later this year. Detector systems are in good shape
 - Polarized Target System
 - All polarized target subsystems are fully operational
 - Spectrometry:
 - All detectors are fully operational, chambers on ArCO₂
 - Cryogenic System
 - Helium production plant, superconducting magnet fully operational
 - Beamline
 - Tests of upstream beamline complete
 - NM2 power supply checks and repairs complete
- Very good collaboration with ESH during the last year
 - Completed review of all procedures
 - Approved to store a small amount (10g) of ammonia to practice target handling
 - Finalizing plans for storage of larger ammonia volume and post-irradiation
- Need to complete reviews before beginning beam operations
 - SAD/ASE review along with Muons/SY/Meson later this month
 - Accelerator Readiness Review in February



Fermilab Facility for Dark Matter Discovery (F2D2)

- PIP-II beam dump facility to host dark sector ASTAE experiments, aligned with P5

New Initiative: A Portfolio of Agile Projects to Search for Direct Evidence of New Particles

the hidden sectors through the Vector and Heavy Neutral Lepton portals. At Fermilab, PIP-II is expected to make many more protons than needed for DUNE, and we anticipate proposals for experiments using the excess protons. These experiments should compete in the portfolio for agile projects (see Recommendation 3a and Section 6.2).

- White paper from the [workshop](#) on physics program, experiments contains proposals for dark sector particle discovery w/ the PIP-II beam w/ strong Fermilab leadership
 - [DAMSA: Very short baseline beam dump experiment](#)
 - [OSCURA: Skipper CCD, low threshold](#)
 - [PIP2-BD: 100t LAr Scintillator](#)
 - [And other opportunities](#)
- Could provide a steady stream of scientific results in the ACE-MIRT era
- Forming a task force to develop a more detailed picture of what would be required to be realize these opportunities



Physics Opportunities at a Beam Dump Facility at PIP-II at Fermilab and Beyond

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Looking ahead from the 2023 P5 Report

Recommendations in new P5 report line up very well with plans of PPD and expertise of our staff



1. Reaffirming the previous P5 recommendations
 - a. Completion of High Luminosity LHC including AUP and CMS/ATLAS detectors
 - b. The first phase of DUNE and PIP-II
 - c. Rubin/LSST
 - d. Continuing support for medium-scale experiments including NOvA, SBN, SuperCDMS, DESI, and Mu2e
2. Constructing a portfolio of new major initiatives
 - a. CMB-S4
 - b. DUNE Phase 2
 - c. Higgs Factory
3. Create an improved balance between small-, medium-, and large- scale projects
 - a. Implement a new small-project portfolio at DOE, ASTAE, which should start with the construction of DMNI experiments (OSCURA, ADMX-EFR)
4. Comprehensive effort to develop the resources ... essential to our 20-year vision for the field. This includes an aggressive R&D program that ... could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.
 - b. Enhance research in theory to propel innovation, maximize scientific impact of investments in experiments, and expand our understanding of the universe
 - e. Conduct R&D efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and Line Intensity Mapping

Summary

- The Particle Physics Directorate has a broad and exciting physics program across all frontiers, supported by close collaboration with theory, that has maintained close alignment with the recommendations of the 2014 P5 report
- Many new results were published in 2023 from both short- and long-baseline neutrino experiments, g-2, CMS, and our astrophysics experiments
- Expect two new experiments to come online in 2024 (SBND, 2x2) and many new results to be published
- This suite of experiments promises ongoing physics results throughout the era leading up to DUNE
- Looking ahead, the recommendations of the 2023 P5 report support the planned program of PPD through the next decade

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